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PV-DIESEL HYBRID ENERGY SYSTEMS FOR REMOTE AREA POWER GENERATION—A REVIEW OF CURRENT PRACTICE AND FUTURE DEVELOPMENTS

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Abstract—The continuous decline of costs for renewable energy technology, together with the establishment of a mature alternative energy industry, has led to the increased utilisation of renewable energy sources for remote area power generation. Rural households in industrialised and less developed countries attach high value to a reliable supply of electricity even if its capacity is limited. The paper reviews the current state of the design and operation of stand-alone PV-diesel hybrid energy systems. It highlights future developments, which have the potential to increase the economic competitiveness of such systems and their acceptance by the user. © 1998 Elsevier Science Ltd.

1. INTRODUCTION

One of the most promising applications of renewable energy technology is the installation of hybrid energy systems in remote areas, where the cost of grid extension is prohibitive and the price for fuel increases drastically with the remoteness of the location. Renewable energy sources, such as photovoltaic, wind energy, or small scale hydro, provide a realistic alternative to engine-driven generators for electricity generation in remote areas [1–3]. It has been demonstrated that hybrid energy systems can significantly reduce the total life-cycle cost of stand-alone power supplies in many situations, while at the same time providing a more reliable supply of electricity through the combination of energy sources [4, 5]. The widely used term Hybrid Energy System (HES) describes a stand-alone energy system, which combines renewable and conventional energy sources with lead-acid batteries for chemical storage. Alternatively, such systems are known as Integrated Renewable Energy Systems (IRES). These classifications do not include single-diesel, multiple-diesel, or diesel-battery systems, which also belong to the broad category of Remote Area Power Supplies (RAPS)[1].

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[1] Hybrid energy systems are a subclass of remote area power supplies.

Numerous hybrid energy systems have been installed in many countries over the last two decades, resulting in the development of systems that can compete with conventional, fuel-based remote area power supplies in many applications. Hybrid energy systems are now becoming an integral part of the energy planning process to supply previously unelectrified remote areas with electricity in countries such as India [6], Thailand [7], Spain [8], South Africa [9], or Australia [10, 11]. An expanding renewable energy industry has developed reliable and cost-competitive systems for remote area power generation. Research has focused on the performance analysis of demonstration systems and the development of efficient power converters, such as bi-directional inverters, battery management units, or maximum power point trackers [12–14]. Simulation programs are available, which allow the optimum sizing of hybrid energy systems based on a life-cycle cost optimisation: Rapsim2 [15], Hybrid2 [16] Pvform [17], or Somes [18].

The current state of hybrid energy system technology is the result of activities in a number of research areas, such as:

- Advances in electrical power conversion through the availability of new power electronic semiconductor devices, have led to improved efficiency, system quality and reliability;
- Development of versatile hybrid energy system simulation software;
- Continuing advances in the manufacturing process and efficiency of photovoltaic modules;
- The development of customised, automatic controllers, which improve the operation of hybrid energy systems and reduce maintenance requirements;
- Development of improved, deep-cycle, lead-acid batteries for renewable energy systems;
- Availability of more efficient and reliable AC and DC appliances, which can recover their additional cost over their extended operating lifetime.

It is the aim of this paper to review the current state of the design and operation of hybrid energy systems, and to present future developments, which will allow a further expansion of markets, both in industrialised and less developed countries. This report concentrates on the application of PV-diesel hybrid energy systems, which account for the majority of systems installed today. One of the inherent advantages of photovoltaic electricity generation is the absence of any mechanical parts (unless tracking of the sun is included). Professionally installed PV arrays are characterised by a long service lifetime, exceeding 20 years, high reliability, and low maintenance requirements, which are highly desirable for remote area power supplies. In sunny locations, PV generators compare favourably with wind generators, despite the higher investment cost for photovoltaic modules per peak Watt. Wind generators require regular maintenance and are susceptible to damage in strong winds. However, the general system configurations presented in section 3 can be expanded to integrate other renewable energy sources, such as wind or hydroelectric generators, which should be considered where the environmental conditions favour their application. Specialised topics, such as the management and performance of lead-acid batteries or modern inverter technology will not be discussed in detail in this review paper.

2. COMPARATIVE ANALYSIS OF THE DESIGN AND OPERATION OF HYBRID ENERGY SYSTEMS

Applications of hybrid energy systems range from small power supplies for remote households, providing electricity for lighting and other essential electrical appliances, to

village electrification for remote communities. In Australia alone, the potential market for hybrid energy systems supplying remote homesteads is estimated to be at least in the order of 10,000 systems [19]. Globally, more than two billion people live without any supply of electricity. For many of these remote communities, renewable energy remains the only realistic alternative to traditional forms of energy use, such as wood or biomass for cooking and heating. At present, the high cost of photovoltaic modules and wind generators limits their application in less developed countries to government subsidised rural electrification schemes or aid programs. The significant improvements of rural living conditions, that can be achieved with only a moderate supply of electrical energy, are well documented, and should encourage further development of renewable energy technology.

In the past, power has been generated in remote areas using engine-driven generators. For applications where a reliable, stationary generator set is required, diesel generators are generally preferred. For less frequent use, petrol generators may provide electricity at the lowest overall cost. Engine-driven generators are inherently inefficient when operated at light loads (<30–50% of rated capacity), which can also shorten their lifetime and result in high maintenance costs. Systems providing intermittent power, which only run the generator during periods when a minimum load is exceeded, are not uncommon. Alternatively, "dump loads" can be installed, which deliberately dissipate energy when useful demand is low, thus loading the engine generator to a significant level. Low combustion temperatures during periods of light loads cause incomplete combustion and carbon deposits ("glazing") on the cylinder walls, leading to premature engine wear [14]. Furthermore, conventional diesel-only remote area power supplies have to maintain a minimum level of spinning reserve[2] to cope with sudden load increases, while allowing sufficient time to bring another generator on line.

The typical load pattern for remote area power supplies is characterised by a small to medium base load, with several periods of higher electricity demand during the day. These characteristics explain why a more economical operation of the engine-driven generator can be achieved by shifting the load with the addition of batteries. Excess energy is stored in the form of chemical storage, which can supplement the generator supply during periods of higher load demand or provide the base load at low load demand. These diesel-battery systems have found widespread application in Australia and other countries for remote area power generation.

More recently, the continuous decline of costs for renewable energy technology, together with the establishment of a mature alternative energy industry, has led to the increased utilisation of renewable energy sources for remote area power generation. The use of photovoltaic modules and small to medium size wind generators is common in RAPS systems, whereas small hydroelectric generators are only suitable in some locations. Other renewable energy sources, such as biomass or solar-thermal generators, have yet to prove their market potential for integration into small to medium size systems. Due to the varying availability of both solar and wind energy, the combination of both sources can lead to a more sustained supply of electricity. However, autonomous renewable energy systems either require large battery banks for storage, or the user has to accept the possibility of loss of load during periods of low renewable energy input. Their application is limited to small systems (<1–2 kW_{peak}) or locations where the supply of fuel is restricted or uneconomic, such as National Parks, remote islands or mountainous regions.

[2] Spinning reserve is the extra rotating capacity on line, which overcomes sudden load increases.

An economic and reliable supply of electricity can be provided by combining renewable and conventional energy sources with a battery bank for storage, forming a Hybrid Energy System. In principle, these systems can be classified into two categories:

(a) Systems based primarily on the non-renewable resource, with PV, wind, or hydro electricity supplementing the energy input to supply the base load during periods of low demand, as well as charging the battery bank when excess energy is available. Generally, batteries are recharged daily to a high state-of-charge (SOC) to optimise the operation of the engine-driven generator. The energy output from the renewable sources is considerably smaller than the average daily load requirement and batteries are sized to be cycled periodically to a low SOC.
(b) Systems based primarily on the renewable resource, with the engine-driven generator used as a backup supply for extended periods of low renewable energy input or high load demand. To cover a high percentage of the daily load demand from renewable resources, both the battery bank and the renewable generators have to be significantly larger than in systems described in (a).

Most hybrid energy systems are designed to operate between these two extremes, depending on the location and the economic life-cycle cost analysis for the particular application. It is evident that a further decrease of the cost of renewable energy generators, in particular photovoltaic modules, will shift the general trend to systems relying more heavily on alternative energy sources [4].

Today, the most common application of hybrid energy systems is that of diesel generator augmentation, where the renewable source and the battery bank are sized to reduce the run-time of the engine-driven generator, as well as allowing the load to be shifted to ensure that the generator is substantially loaded [20, 21]. Peak loads can be met by the engine-driven generator together with the stored energy or the renewable generator. Generally, such systems are installed in locations where the logistics and economics of a reliable fuel supply are not a major contributing factor to the overall cost of system operation [22]. The "displacement-type" system is sized to reduce the fuel consumption of the diesel generator by 70–90%, therefore, relying heavily on the renewable resource. The engine-driven generator remains in the system to equalise the battery banks[3] and to act as a backup generator for extended periods of low renewable energy input or high load demand. Such systems are preferred in locations where fuel supplies are expensive or unreliable [20]. Figure 1 shows a generalised model of a parallel hybrid energy system.

The configuration of a hybrid energy system depends on the environmental conditions, which have to be considered for the life-cycle cost analysis, and the particular requirements of the customer. Use of a bi-directional inverter for both DC–AC and AC–DC conversion eliminates the need for both an inverter and rectifier. Individual system components may require designated controllers, which safeguard the operation of these components and hence maintain operation of the complete system.

Hybrid energy systems have advantages over conventional remote area power supplies where the load demand over the day is highly variable. A recent study of systems installed in the U.S.A. by Durand [23] concludes that hybrid energy systems are cost-competitive

[3] Regular boost charging of flooded-electrolyte lead-acid batteries every 2–6 weeks is recommended by most battery manufacturers to prolong their service lifetime.

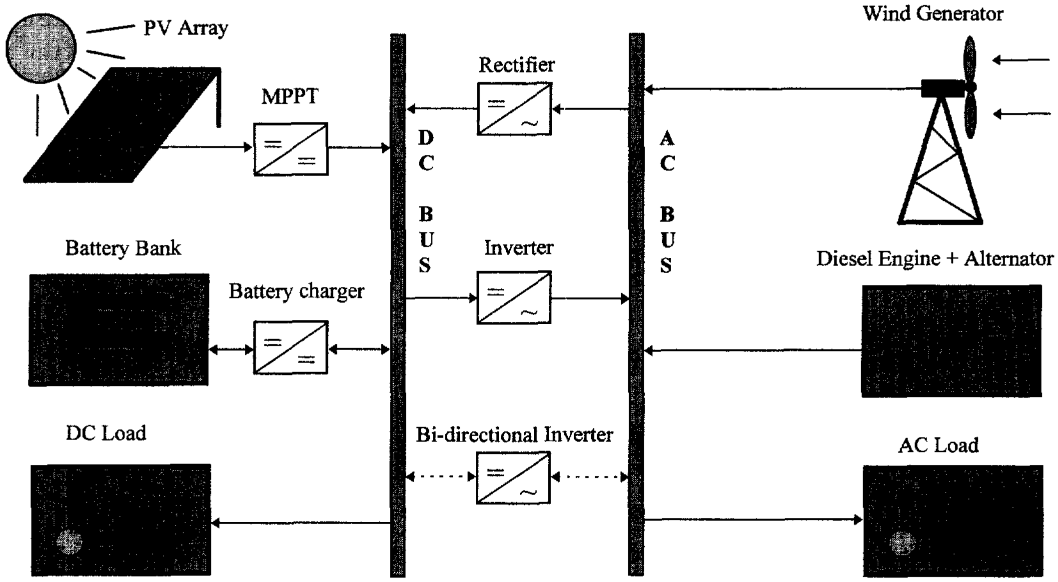

Fig. 1. Hybrid energy system configuration (system topology adopted from [16]).

with conventional systems where the ratio of heavy to light loads exceeds 3 : 1. If the load variability is less pronounced, then other constraints such as limited access or restricted environmental impact may favour the application of renewable energy sources for remote area power generation. While this general conclusion does not substitute the need for a detailed life-cycle analysis for other locations or different operational conditions, it indicates that there is a large potential market for this emerging technology in the U.S.A. and other countries. Experience has shown that conventional diesel systems are often not flexible enough to respond to the changing load demand and varying operating conditions. In the past, this has resulted in compromises regarding the efficiency and supply quality, pending substantial upgrades of engine-driven generators. Significant changes of short and long-term load demand patterns are frequently experienced as a result of [11]:

- Increasing or decreasing population;
- Changing consumer trends (e.g. increased use and number of electrical appliances);
- Special community events;
- Seasonal changes of environmental conditions (e.g. temperature, humidity).

In contrast, renewable energy sources and batteries are inherently modular and can generally be upgraded when the long-term load demand increases, without changing the overall configuration of the system. Power electronic converters, such as inverters, maximum power point trackers, or battery chargers, should be sized so that an anticipated increase in load demand does not exceed their rated capacity, or they could be of modular design. System availability is improved by the inherent redundancy of hybrid energy systems. Either the inverter or the engine-driven generator may be used to meet the critical loads during unscheduled maintenance [24], which can be of great importance for applications such as the refrigeration of vaccines or the supply of electricity for remote hospitals.

To conclude this analysis of supply options for rural and remote area power generation, a comparison of RAPS systems with grid-extension is presented in Table 1. A survey of residents living in remote areas of New South Wales, Australia, provides an interesting comparison of such systems [25]. It needs to be emphasised that remote area power generation will remain expensive, regardless of the system type that is chosen. A life-cycle cost analysis of different supply options has to take into account the availability and cost of fuel over the entire lifetime of the system, it has to assess the renewable resources on a seasonal basis, consider the operating conditions, user preferences and requirements, and the availability of modern system technology together with adequate technical support.

3. PV-DIESEL HYBRID ENERGY SYSTEM CONFIGURATIONS

PV-diesel hybrid energy systems generate AC electricity by combining a photovoltaic array with an inverter, which can operate alternately or in parallel with a conventional engine-driven generator. They can be classified according to their configuration as [14]:

(a) Series hybrid energy systems;
(b) Switched hybrid energy systems;
(c) Parallel hybrid energy systems.

An overview of the three most common system topologies is presented by Bower [20]. In the following comparison, typical PV-diesel hybrid system configurations are considered.

3.1 *Series configuration*

All the energy is passed through the battery bank and the AC power delivered to the load is converted from DC to regulated AC by an inverter or a motor generator unit as shown in Fig. 2. The system can be operated in manual or automatic mode, with the addition of an appropriate battery voltage sensing and start/stop control of the engine-driven generator.

Advantages

- No switching of AC power between the different energy sources is required, which simplifies the output interface;
- The power supplied to the load is not interrupted when the diesel generator is started;
- The inverter can be sine-, quasi-sine or square-wave, depending on the application[4];
- The engine-driven generator can be sized to be optimally loaded while charging the battery bank, until a battery state-of-charge of 75–85% is reached.

Disadvantages

- The inverter cannot operate in parallel with the engine-driven generator, therefore, the inverter must be sized to supply the peak load of the system;
- The battery bank is cycled frequently, which shortens its lifetime;
- The cycling profile requires a large battery bank to reduce the depth-of-discharge;

[4] In recent years, there has been a clear trend towards sine-wave inverters, which offer superior power quality compared with square- and quasi-sine wave inverters at a moderate additional cost [4]. Square-wave inverters are not recommended for many household appliances.

Table 1. Comparison of supply options for rural and remote area electrification

System type	Advantages	Disadvantages
Grid extension	Ability to respond to changes in load demand without the need for system upgrades (within certain limits). Quiet operation. Established, familiar technology. No emissions where electricity is used. Most rural customers prefer to be connected to the electrical grid network.	Rural transmission lines are uneconomic (they usually need to be subsidised). Low quality of grid supply at the end of long transmission lines. High maintenance costs. Environmental impact of transmission lines (land use, maintenance roads).
Diesel-only RAPS (Single-diesel or multiple-diesel)	Straightforward system design and operation. Established, familiar technology. Economic for systems where fuel is available at low to medium cost. Reliable if maintained by trained operators.	Reliance on medium fuel prices. High maintenance cost for DG operation. Low efficiency and increased wear at part load operation. Limited service lifetime of DG. Pollution through toxic fumes, noise, or fuel spillage. Limited flexibility to respond to changing load demand and operating conditions.
Diesel-battery RAPS	Improved efficiency of DG operation leads to reduced fuel consumption. Reduced number of operating hours, allowing restricted operation at night-time. Peak loads can be supplied by DG together with the inverter in parallel.	Additional complexity and cost for battery storage and power electronic converters. Automatic control highly recommended. Flooded electrolyte lead–acid batteries need regular maintenance. Moderate flexibility to respond to changing load demand and operating conditions. Pollution through toxic fumes, noise, or fuel spillage. High maintenance cost for DG operation.
Hybrid energy system	Reduced maintenance requirements for DG. Reduced fuel consumption through additional renewable energy sources. Inherent modularity of renewable energy sources allows convenient system upgrades. Can be the most economic option where fuel is expensive and renewable resource is good. Reduced impact on environment. Flexibility to respond to short and long term load fluctuations. Potentially more reliable supply than grid-extension if well designed and maintained.	Additional investment cost and complexity for renewable energy sources, batteries, and specialised power electronic converters. Limited experience of customers and supply authorities with renewable energy systems. Automatic energy management system required to ensure efficient system operation. Potential lack of technical or financial support. Flooded electrolyte lead–acid batteries need regular maintenance. System configuration should be based on life-cycle cost analysis, which requires detailed system simulations.

DG = diesel generator.

- Reduced overall efficiency, since all energy flows through the battery and the inverter;
- Inverter failure results in complete loss of power to the load.

3.2 *Switched configuration*

Despite its limitations, the switched configuration shown in Fig. 3 remains one of the most common installations today [20]. It allows operation with either the engine-driven alternator or the inverter as the AC source, yet no parallel operation of the main generation sources is possible. The battery bank can be charged by the diesel generator and the renewable energy source. The load can be supplied directly by the engine-driven generator, which results in reduced cycling of the battery bank. It can be operated in manual mode, although the increased complexity of the system makes it highly desirable to include an automatic controller, which can be implemented with the addition of appropriate battery voltage sensing and start/stop control of the engine-driven alternator.

Advantages

- The inverter can be sine-, quasi-sine or square-wave, depending on the application;
- Both energy sources can power the load directly.

Disadvantages

- Power to the load is interrupted momentarily when the AC power sources are transferred;
- The engine-driven alternator and inverter have to be designed to cope with the peak load;
- No optimised allocation of fuel-based and renewable resources is possible.

3.3 *Parallel configuration*

The parallel configuration shown in Fig. 4 allows all energy sources to supply the load separately at low or medium load demand, as well as supplying peak loads from combined sources by synchronising the inverter with the alternator output waveform. The bi-directional inverter can charge the battery bank (rectifier) when excess energy is available from the engine-driven generator, as well as act as a DC–AC converter (inverter) under normal operation. The bi-directional inverter may provide peak shaving as part of the control strategy when the engine-driven alternator is overloaded.

As stated in a comparison of hybrid energy systems by Nayar *et al.* [14], the parallel configuration offers a number of advantages over other system topologies:

- The system load can be met in an optimal way;
- Diesel efficiency can be maximised;
- Diesel maintenance can be minimised;
- A reduction in the rated capacities of the diesel generator, battery bank, inverter, and renewable resources is feasible, while also meeting the peak loads.

These objectives can only be met if the interactive operation of the individual components is controlled by an "intelligent"[5] hybrid energy management system. Although today's generation of parallel systems includes system controllers of varying complexity and sophis-

[5] The term "intelligent" refers to the application of Artificial Intelligence to the operational control of hybrid energy systems. Advanced system controllers may include Fuzzy Logic, Artificial Neural Networks, or Expert knowledge to optimise the decision making process.

tication, they do not optimise the performance of the complete system. The parallel hybrid energy systems currently available may include the following control functions:

- Control of energy flow based on load demand (e.g. low, medium, high load demand);
- Battery low voltage disconnect to prevent excessive discharging;
- Controlled battery charging to ensure fast recharging, while avoiding "gassing" due to overcharge;
- Controlled "boost-charging" of flooded electrolyte lead-acid batteries at regular intervals (2–6 weeks) to reduce the negative effects of electrolyte stratification;
- Battery management based on voltage measurements to estimate the state-of-charge (SOC);
- Controlled bi-directional energy flow through the inverter to allow the charging of the battery bank from non-renewable resources at medium load demand, when excess energy is available from the engine-driven generator, which is operated at its maximum efficiency;
- Automatic start/stop control of the engine-driven generator;
- Load sharing between the inverter and the engine-driven generator.

It is interesting to note that most commercially available parallel hybrid energy systems implement these control functions as part of the microcontroller which is used to synchronise and control the bi-directional inverter [13, 14]. While this may be a cost-effective solution, it forces the customer to rely on the supplier of the inverter to design the complete system, thereby reducing the modularity of the individual system components. Furthermore, it suggests that the system controller is designed as an additional feature, rather than the central management unit of the complete parallel hybrid energy system. As emphasised by Sachau, "to achieve cost reductions and improved reliability, standardization at the component level should be aimed at. [It]... is now considered to be a more satisfactory solution than standardization at the level of the system" [26]. This implies, that the concept of "modular system technology" should be applied to the design of hybrid energy systems. "It is important to proceed from the basic demonstration stage of PV power supply towards a system technology for a whole range of applications, which... promotes the series production of subsystem units for use as flexibly integrateable system components" [27].

In recent years, major performance improvements of hybrid energy systems were due to:

- Increased conversion efficiency of photovoltaic modules and small to medium size wind generators;
- Development of maintenance-free, sealed lead-acid batteries for renewable energy systems;
- Customised solution for a wide range of applications;
- Increased competition and experience in the field resulted in significant progress to produce efficient, reliable standard components for use in renewable energy systems, such as bi-directional inverters, maximum power point trackers, or battery chargers.

Further improvements can be achieved through optimal design and control of hybrid energy systems, which will be discussed in the following section. To conclude this review of hybrid energy system topologies, it should be emphasised that only the parallel configuration allows the implementation of an optimal[6] control strategy, which has the potential to significantly improve the performance of the complete system.

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[6] The term "optimal" is used to describe the design and operation of a parallel hybrid energy system, which allocates renewable and field-based resources in such a way that it results in minimum life-cycle costs, while also considering restrictive operational conditions.

4. ENERGY MANAGEMENT, SIZING AND CONTROL OF HYBRID ENERGY SYSTEMS

The design process of hybrid energy systems requires the selection and sizing of the most suitable combination of energy sources, power conditioning devices, and energy storage system together with the implementation of an efficient energy dispatch strategy. "In order to achieve a larger penetration of renewable resources, without deterioration of the quality of service offered to customers, the development of new control tools is necessary..." [28]. System simulation software [15, 16] is an essential tool to analyse and compare possible system combinations, which are limited by:

- Environmental conditions at location (irradiance, temperature, wind speed, humidity);
- Customer requirements and preferences;
- Financial resources of customer and availability of government support schemes;
- Availability of reliable system technology and technical support.

As stated in a report by MacGill [29], "the possible range of often poorly defined user objectives, the highly variable and unpredictable nature of renewable energy sources and remote user loads, and the complex behaviour of lead-acid batteries all lead to challenging problems in optimising the design and on-going operation of RAPS systems". The energy management system has to address conflicting objectives of system operation:

- Maximise system efficiency;
- Minimise fuel consumption of engine-driven generator;
- Maximise utilisation of renewable resources;
- Maximise service life of system components;
- Safeguard reliable operation of the system;
- Consider operational constraints, such as load priorities, restricted night-time operation of the diesel generator, or minimum battery state-of-charge.

Two main aspects of control strategies need to be considered for hybrid energy systems:

(a) Energy dispatch strategy, which is concerned with the allocation of resources and the direction of power flow in the system on a timescale of minutes to days;
(b) Power quality control, which is concerned with the stability of the AC voltage and its total harmonic distortion (THD) on a timescale below the time period defined by the supply frequency.

An interesting discussion of various dispatch strategies by Barley [30] compares their application to the control of wind–diesel hybrid energy systems, based on a lifecycle cost analysis. Batteries may be discharged to satisfy transient loads or to supply all or part of the average load, therefore, providing significant operational freedom for the energy management of remote area power supplies. Two commonly applied methods are identified by Baring-Gould [16] as the transient peak strategy and average load strategy, which are also referred to as the peak shaving and cycle charge dispatch strategies, respectively. "The transient peak strategy seeks to use energy from storage to ensure that the number of diesels that are on is determined solely by the average net load[7] rather than the maximum net load

[7] Net load is defined here as the load demand less the available power from the renewable sources.

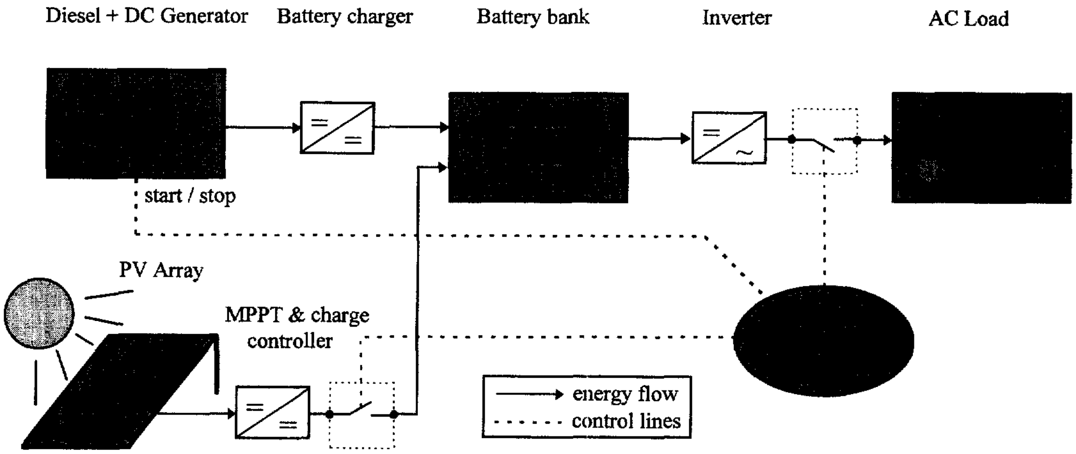

Fig. 2. Series PV–diesel hybrid energy system.

during the interval. Thus short term increases in load do not require starting a new diesel... If shutting off of all the diesels is allowed[8] and the average net load is less than zero, and if there is enough storage to supply all the positive instantaneous net load then all diesels may be off... The average load strategy control option is similar to the transient peak strategy in that it uses storage to select which diesels are on. In this case, however, it seeks to use storage to the maximum extent. It does this by shutting off as many diesels as possible, subject to the availability of stored energy... (unless) recent operating history does not allow all the diesels to be shut off (because the minimum run time has not elapsed)..." [16].

Figure 5 gives an example of the energy dispatch for a PV dual-diesel system, which is operated using the transient peak strategy. This dispatch strategy lends itself to applications where the renewable energy contribution and battery storage capacity are moderate. Figure 6 shows the energy dispatch for a PV single-diesel system, which is operated using the average load strategy. The diesel generator is run for a limited time at rated power. To reduce the required battery storage capacity the photovoltaic energy input is significantly larger.

Many variations of these energy dispatch strategies are possible [30]. The selection of the most efficient control algorithm depends on fuel, maintenance and component replacement costs, the system configuration, environmental conditions, as well as the constraints imposed on the operation of the hybrid energy system. Further research is needed to derive general guidelines for the selection of the most appropriate method from a range of possible dispatch strategies. Detailed system simulations under realistic operating conditions allow the comparison of the total life-cycle cost for different applications. Power quality control is not discussed as part of this report, due to the complexity of the topic, other than to note

[8] In conventional AC bus diesel networks, and in many hybrid power systems, a synchronous generator connected to a diesel is needed to supply reactive power. In any system with an AC bus at least one diesel should normally be kept on, unless some other option is provided to supply reactive power and maintain the grid frequency.

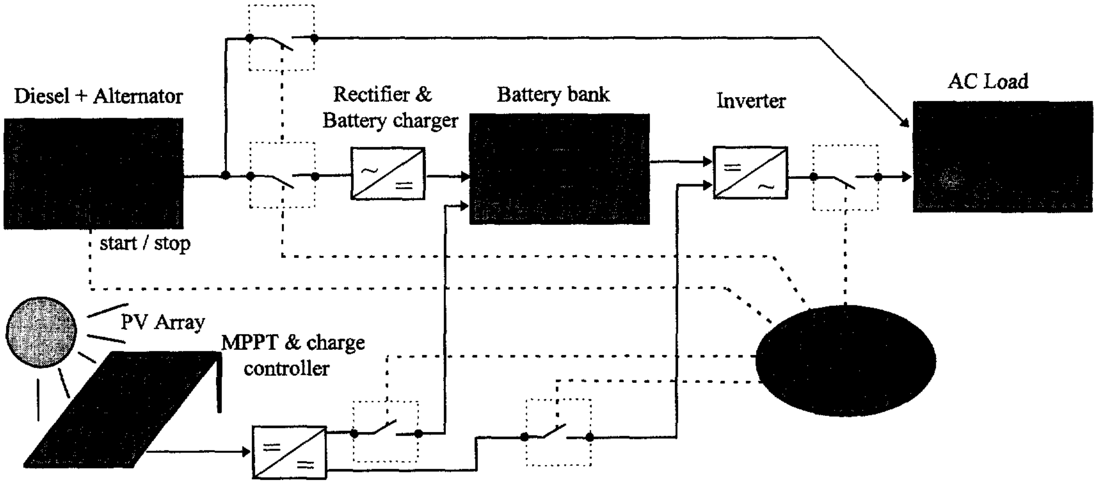

Fig. 3. Switched PV–diesel hybrid energy system.

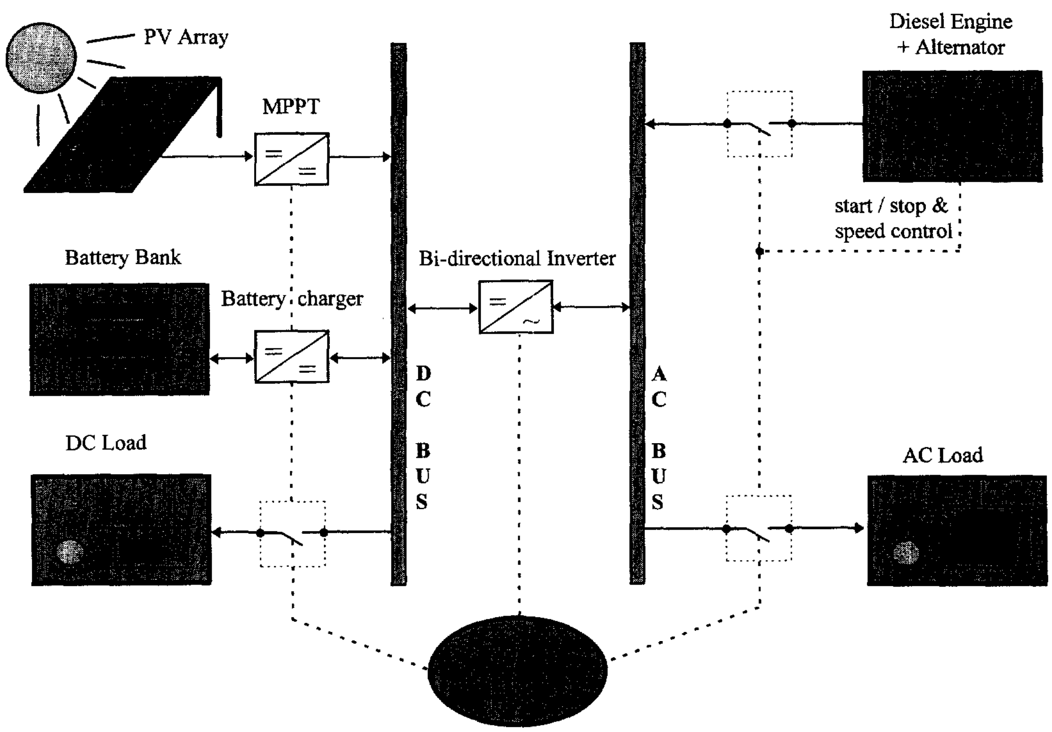

Fig. 4. Parallel PV–diesel hybrid energy system.

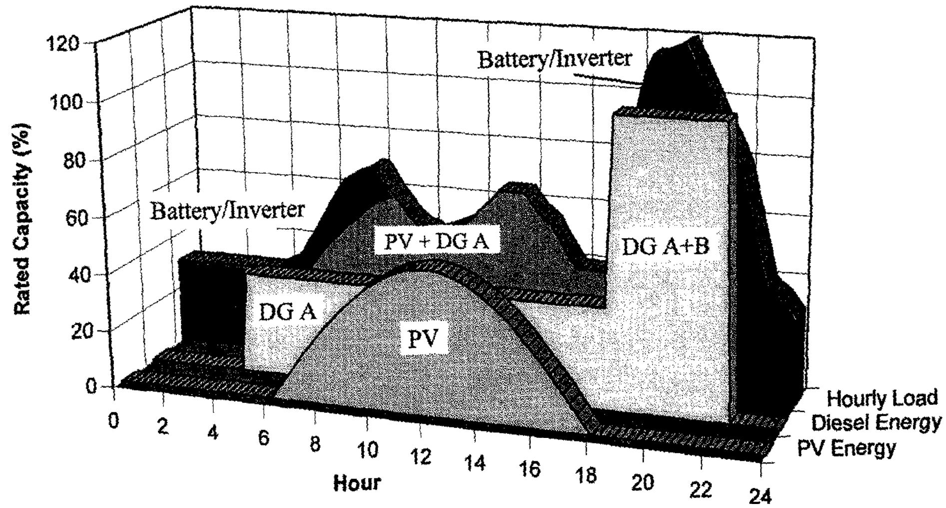

Fig. 5. Energy dispatch of a PV dual-diesel system using the transient peak strategy.

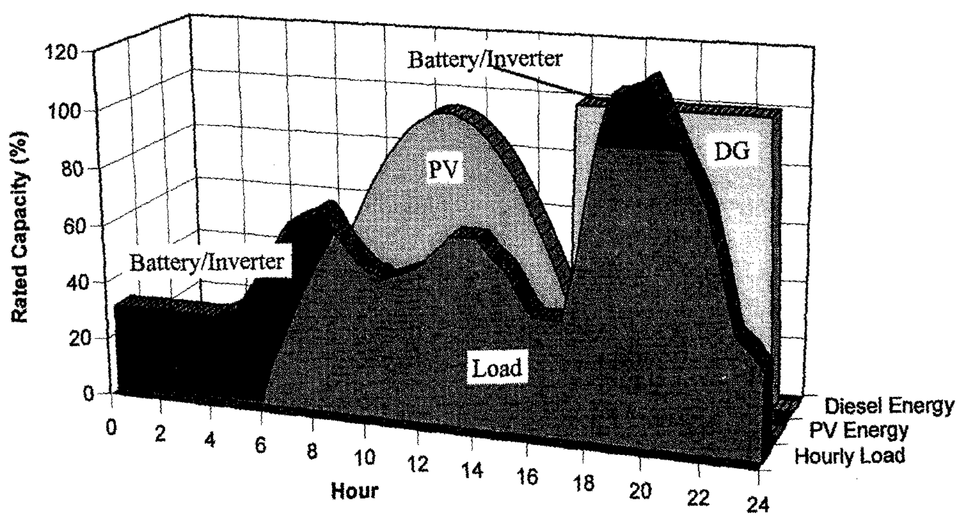

Fig. 6. Energy dispatch of a PV single-diesel system using the average load strategy.

that inverters using pulse-width-modulation techniques inherently produce voltage and current waveforms with low harmonic content.

The two system components which are most susceptible to damage from non-ideal operating conditions are the engine-driven generator and the battery bank. To minimise the total life-cycle cost of the system, they need to be controlled according to well-defined operational procedures. Part load operation of the diesel generator should be avoided, since it results in increased maintenance requirements and wear of mechanical parts, as well as

being inefficient. Frequent start/stop cycles can also reduce the service lifetime of diesel generators.

In most conventional applications, lead–acid batteries are charged either by a constant voltage, or a constant current source. Various algorithms optimise the efficiency and duration of the charge cycle by implementing combinations of these two methods. High current charging is performed until the battery reaches approximately 80% of the maximum state-of-charge. Further charging at high currents has detrimental effects on the battery performance, which are avoided by controlled charging with a reduced current. In many hybrid energy systems, this results in inefficient operation of the diesel generator or reduced utilisation of the renewable resource. To account for the difficulties experienced when charging battery banks in hybrid energy systems, the following functions have to be included in an advanced battery management system:

- Efficient charging algorithm from combined or separate energy sources for fast recharging without overcharging or "gassing", taking into account the varying energy input from renewable resources and the operating characteristics of the engine-driven generator;
- Minimum discharge level protection to prevent detrimental effects on battery performance;
- Controlled overcharging of flooded electrolyte lead-acid batteries ("boost charging") at regular intervals every 2–6 weeks to reduce the negative effects of electrolyte stratification.

In recent years, further improvements of battery performance have been reported by implementing additional charge and discharge procedures for chemical storage systems, including [31–34]:

- Charge equalisation between individual battery cells;
- Split battery charging algorithms, which divide the battery bank into several independent blocks to provide a larger degree of freedom for system operation;
- Hybrid battery configurations, combining various types of batteries with different performance characteristics, which can be allocated to perform specialised tasks.

Although these advanced features increase the complexity of hybrid energy systems, their potential to improve the performance and cost effectiveness should be investigated through field trials and inclusion in system simulations.

A widely studied approach to optimise the operation of hybrid energy systems is to minimise the life-cycle cost of hybrid energy systems by allocating realistic costs for the purchase of system components, fuel consumption, maintenance requirements, and component replacement. Such economic optimisation algorithms have been applied to the sizing and design of hybrid energy systems [2, 35–38] and are expected to be integrated into hybrid energy system simulation packages in the near future. Hardware implementation of optimal control algorithms requires the design of an "intelligent" energy management system, which involves the application of Artificial Intelligence to the operation of hybrid energy systems [28, 29]. Today's microcontroller technology allows the integration of complex control strategies, which can be designed to optimise the operation of parallel hybrid energy systems. Optimum resource allocation, based on load demand and renewable resource forecast, promises to significantly reduce the total operating cost of the system. This can be achieved through the development of an adaptive control unit, which decides on the commitment of renewable and non-renewable resources to improve overall system efficiency [39]. The potential for performance improvements, due to an "optimal" control strategy

compared with a "best" dispatch strategy is the subject of debate [29, 30]. Further research, based on detailed modelling of hybrid energy systems under realistic test conditions, is needed to assess the economic advantage of the inclusion of "intelligence" as part of the energy management system [40].

While it is evident that system efficiency and life-cycle costs are crucial factors for the sizing and operation of hybrid energy systems, more emphasis needs to be placed on their user-friendliness. It is one of the main advantages of hybrid energy systems over conventional systems for remote area power generation, that the combination of energy sources with energy storage provides considerable freedom to integrate operational constraints in the decision-making process. Cost-optimisation algorithms have limited potential to address qualitative performance objectives, such as minimal environmental impact through noise or toxic fumes, optimum utilisation of renewable resources, loss of load "acceptability",[9] or the preferential servicing of high priority loads. Additional features, such as the design of a "smart" user-interface to support active load management by the consumer, therefore, adapting the demand pattern to the available renewable resource, have the potential to make hybrid energy systems an increasingly attractive option for remote area power generation [8, 29, 41].

5. FUTURE TRENDS FOR THE DESIGN AND OPERATION OF HYBRID ENERGY SYSTEMS

At present, hybrid energy systems range from small, "do-it-yourself" systems (which may satisfy both the electrical load and the technical curiosity of their users) to highly sophisticated, professional systems installed to provide remote communities with reliable, grid-quality electricity. Further improvements will allow the extension of markets for this emerging technology, both in industrialised and less developed countries.

Bower [20] lists a number of hardware developments, which are required to achieve further performance improvements, including static power converters, system controllers, and battery charge controllers. Most importantly, power conditioning devices need to be designed to be more efficient at the low end of their operating range. Inverter operation has to be improved for low load demand, which accounts for a significant percentage of the total energy conversion in most hybrid energy systems. Durand [23] proposes the development of inverters with 95% efficiency from 1% to 200% loading, which is a very optimistic target, taking into account the inherent losses of even the most efficient power electronic devices. The inherent modularity of renewable energy sources needs to be considered when designing improved, standardised power conditioning equipment [42]. Today, many systems compromise the modular capabilities of photovoltaic modules and wind generators by including power converters which themselves are not modular, or have an insufficient power rating to allow later system upgrades. Regardless of the performance improvements achieved by modern power electronic converters, reliability of system components has to remain the highest priority for new hardware developments.

As concluded from a survey of residents living in remote areas of New South Wales,

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[9] Users may consider the loss of load to be acceptable under unfavourable operating conditions. This can result in a very high percentage of energy contribution from renewable resources, without the need to oversize the renewable generators or battery storage.

Australia, "for RAPS users the most important problems are load restrictions, generator fumes and noise, maintenance and lack of technical support" [4]. Other issues, such as power quality, supply reliability, insurance, or safety, were identified as less important concerns for the majority of respondents, which indicates a high standard of systems installed in this region. While the technical issues can be addressed by the development of advanced hybrid energy system technology, it must be emphasised that the provision of adequate maintenance and technical support will remain a difficult logistic problem, given the remoteness of many locations. This leads to the demand for systems, which are highly reliable over their entire lifetime, as well as requiring minimum maintenance, preferably by untrained operators. This can be achieved by the development of systems, which are characterised by:

- Maintenance-free[10] energy storage systems;
- Fully automatic energy management system;
- High percentage of energy demand supplied by renewable energy sources, in particular photovoltaic energy;
- Improved reliability of power conditioning devices.

Lead–acid batteries are still regarded as the most economic form of energy storage for the next decade, despite their less than ideal operating characteristics. Progress has been reported on the development of new chemical storage systems, such as hydrogen storage [43, 44], vanadium–redox [45], and zinc–bromine batteries [46], but it remains difficult to assess if it will be economic within the next decade to integrate these storage systems in small to medium size hybrid energy systems.

As discussed in the previous section, the inclusion of Artificial Intelligence as part of the energy management system promises to optimise the operation of hybrid energy systems [40]. The performance of modular hybrid energy systems can be improved through the implementation of advanced control methods in a centralised system controller. Optimum resource allocation, based on load demand and renewable resource forecast, promises to significantly reduce the total operating cost of the system. The application of modern control methods to supervise the operation of modular hybrid energy systems allows the utilisation of the renewable resource to be optimised, while also reducing the fuel consumption of the engine-driven generator. "With smaller remote area power supplies, users can form a rather intimate relationship with their systems and learn to adapt their load demands to its capabilities... Once in operation, the systems get to experience the range of available renewable energy inputs and required load profiles..." [29]. System performance may be further improved by taking advantage of this knowledge through the integration of resource and load forecasting in the overall management of the system.

It will be important to promote the application of hybrid energy systems to rural and remote customers, as well as to the electricity supply industry. Users and system operators need to be provided with adequate information on this alternative energy option. Government support schemes and financing arrangements are effective economic tools to allow customers to pay the high investment costs of hybrid energy systems, which are then recovered over its lifetime through reduced fuel, maintenance, and component replacement

[10] Maintenance-free is a widely used, euphemistic term for very low maintenance energy storage systems.

costs. Increasingly, NGOs are considering the application of renewable technology in remote and rural locations, to provide a clean, reliable, and sustainable form of electricity to the population of less developed countries.

Future hybrid energy systems may replace the engine-driven generator with modern fuel cells, which have a number of advantages [21]:

- High efficiency of energy conversion (40–60%), particularly at part load operation;
- Little or no noxious emissions, depending on the fuel cell type;
- Silent operation;
- Modular construction;
- Ability to utilise most fuels.

Such systems may combine fuel cells with hydrogen storage systems, which would allow the inclusion of seasonal storage, potentially making the system completely independent from the supply of fuel. In the longer term, renewable energy could provide communities with hydrogen fuel for cars, space and water heating, cooking, refrigeration, and reliable supply of electricity during periods of low renewable energy input.

6. CONCLUSION

Increasingly, hybrid energy systems are recognised as a viable alternative to reticulated grid supply or conventional, fuel-based, remote area power supplies. Rural households in industrialised and less developed countries attach high value to a reliable, limited supply of electricity. Community facilities such as rural hospitals, schools, or water pumping stations can contribute significantly to welfare and rural development [9, 47–50]. While it is recognised that technology can only be one aspect of community development, renewable energy systems have the demonstrated potential to provide some of the infrastructure needed in remote areas [51]. Although the cost and technological development of hybrid energy systems in recent years has been encouraging, they remain an expensive source of power. To allow the widespread application of this emerging technology, there is a need for further improvement of the design and operation of hybrid energy systems, as outlined in this report.

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